Optimisation of vehicle concepts in a multimodal environment with regard to user benefit

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ABSTRACT: This paper is about an optimisation tool that outlines a blueprint for a battery electric vehicle and a plan for the best mobility mix based on the user’s mobility behaviour and the available infrastructure. Its core is a modular longitudinal dynamics simulation model that is enhanced by package, battery, weight, aerodynamics, and costs modules. The input data is taken from a trip database that has been recorded on smartphones. The optimisation target is the total mobility costs for the user. Soft factors like comfort, travel time or good vehicle dynamics are implemented as boundary conditions. The tool is meant to provide quantitative input during the vehicle planning phase.

Keywords: Modal split, Multimodal optimisation, Genetic algorithm, User benefit, Electromobility, Package optimisation, modular vehicle simulation model

1. MOTIVATION AND AIM

History shows that all round battery electric vehicles (BEV) are scarcely competitive with conventional vehicles. This is due to high costs and the low volumetric and gravimetric energy densities of the battery systems. The comparison of a Mitsubishi iMiEV and a Volkswagen Polo Blue Motion shows, that an electric powertrain for a compact car, which has the same power and weight as a comparable conventional powertrain, only provides one tenth of the range [1]. Another aspect is the high CO_2 emission released during the production of the BEV's powertrain and during the generation of energy. Limiting the top speed, range and transport capacity of a BEV reduces its costs and emissions during production, use and recycling at the same time. This attempt at intelligent reduction makes vehicle concepts possible, which are competitive with conventional cars with state of the art technology [2]. But this reduction also means that such a vehicle no longer suits all the needs of the user. Today’s cars are developed to fulfil every costumer need. A conventional car may not be perfect for every use case, but there is a minimum of range, storage capacity and comfort, which the majority of all cars provide. Such all round cars are not reasonable or even possible with an electric powertrain. Personal electric transport only makes sense in combination with other modes of transportation. This can, for example, be public transport, car sharing or taxis. The car's performance, which is usually measured by top speed, range, loading capacity and comfort, has to be well fitted to user needs and, as the BEV can’t fulfil all mobility needs, to those trips that are possible with the BEV. Some trips are not possible because of the BEV´s range, seat or luggage capacity. As the modal split is now a new variable, it has to be taken into account during the vehicle's planning phase as well. The difficult question is how big the car has to be and, as a result, where to split the means of transport. One possibility that is usually chosen is to cut the range at some point in order to cover the majority of all trips. Figure 1 shows the distribution of different trip lengths that have been recorded at the Institute of Automotive Technology of the TU München [3]. The selected user is a potential costumer for an electric car with good income and an own garage.

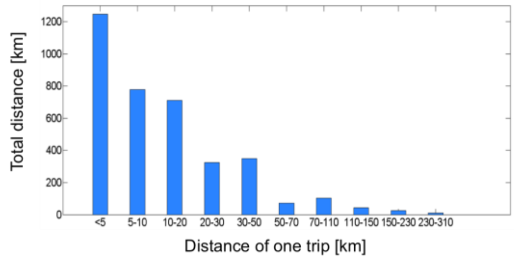

Figure 1: Distribution of different trip lengths [3]

If the BEV is designed for a range of 50 km, the range is sufficient for more than 95% of the trips. The difficulty is that the range might not be the only limiting factor. Other limits include the amount of seats or the storage capacity. This is not something specific to electric cars, but especially important for BEVs because their design has to fit the user's needs very precisely in order to gain an advantage over conventional vehicles. The challenge is to find the best compromise between a very simple small car and a big over-engineered car in the multidimensional field of vehicle properties and modes of transport. This paper describes an approach based on an optimisation algorithm. The aim is to create a tool that helps to find the best vehicle topology in the product planning phase. The underlying vehicle, infrastructure, technology and cost models give a better understanding of technical feasibility and show the influences of different scenarios on the vehicle and the potential market. This approach avoids conceptual mistakes in the early planning phase that would be very difficult and expensive to correct later.

2. OPTIMISATION STRATEGY

The introduction shows that the planning of a BEV should not be done without considering the influence of alternative modes of transportation. Thus, the optimisation approach, described in this paper, joins BEV technology with boundary conditions set by the available mobility mix. Possible alternatives are public transport, car sharing and the use of taxis. The boundary of the modelled system includes the BEV and all those possible alternatives. Figure 2 shows the system boundary, the included components and the system inputs and outputs.

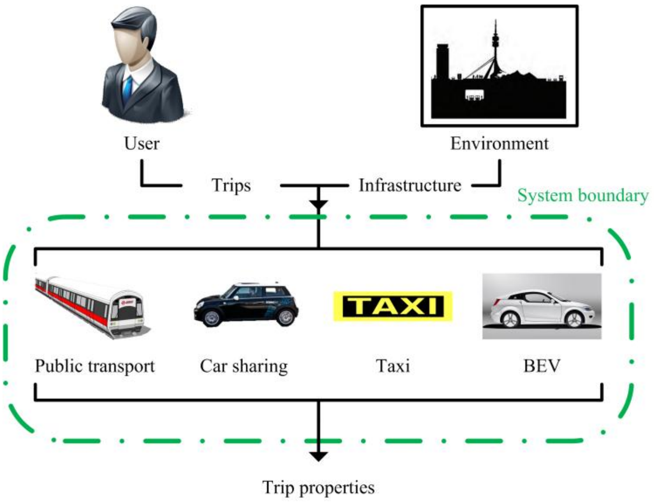

Figure 2: System boundary

The input to the system is a collection of trips the user wants to take and the environment they are completed in. This trip data was recorded with the internal GPS and acceleration sensors of smartphones [3]. The dataset of one trip consists of a questionnaire block and a time position, speed and acceleration log. The questionnaire block includes information about the number of passengers, the amount of luggage, the purpose of the trip and the mode of transportation. All trips are stored in a central database. During a time period of 17 months, 6000 trips of 100 frequent users were recorded. The selected users are potential customers for battery electric vehicles. Their income is above average and they have access to their own garage with the possibility to charge the car. It is assumed that the driving behaviour of the users does not change due to the electrification of the vehicle. This is based on the fleet tests BMW carried out with electric Minis.[9]

For vehicle concept optimisation, every single trip is analysed for every mode of transportation separately. In order to do this, the four modes of transport are represented by independent simulation models. The time, position, speed and time log of the trips is used to simulate the BEV or calculate the costs and duration for taxi, car sharing or public transport. The results are different properties of the journeys. The questionnaire data is used to check whether the respective mode of transport is possible.

The central idea is to solve the mobility problem of the user in one optimisation process. Taken over a certain period of time, a given mobility solution creates benefit and costs for the user. There are several trip properties that are responsible for this benefit. Figure 3 shows the most important ones.

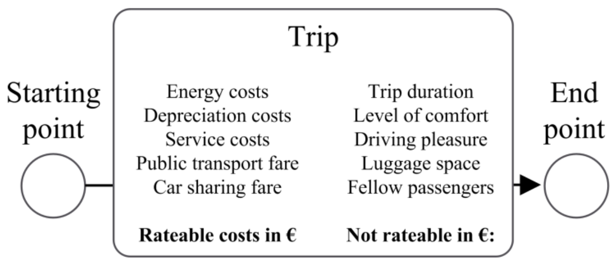

Figure 3: Properties of a journey

The main benefit is to reach the destination. Besides that, the duration of the journey, the level of comfort, the driving pleasure, the storage capacity and the capacity for fellow passengers are important and evaluated in the mobility models. Every mode of transport creates a different level of comfort for every trip depending on the weather and other factors. As these properties are difficult to describe and weighed as one target function, the costs are set as the optimisation target. Most of the journey properties, however, are opposed to the mobility costs. The optimised solution would be rated very badly with these soft properties. No user would accept a car whose development is purely cost driven. In order to also maintain a good rate of benefits to the user, several boundary conditions that describe these soft properties, like travel time, are implemented. The benchmark he is used to is given through the trip database that is recorded with conventional vehicles. The optimised solution should provide the same flexibility and comfort the user would experience with a conventional multi purpose vehicle. Figure 4 shows the complete optimisation process.

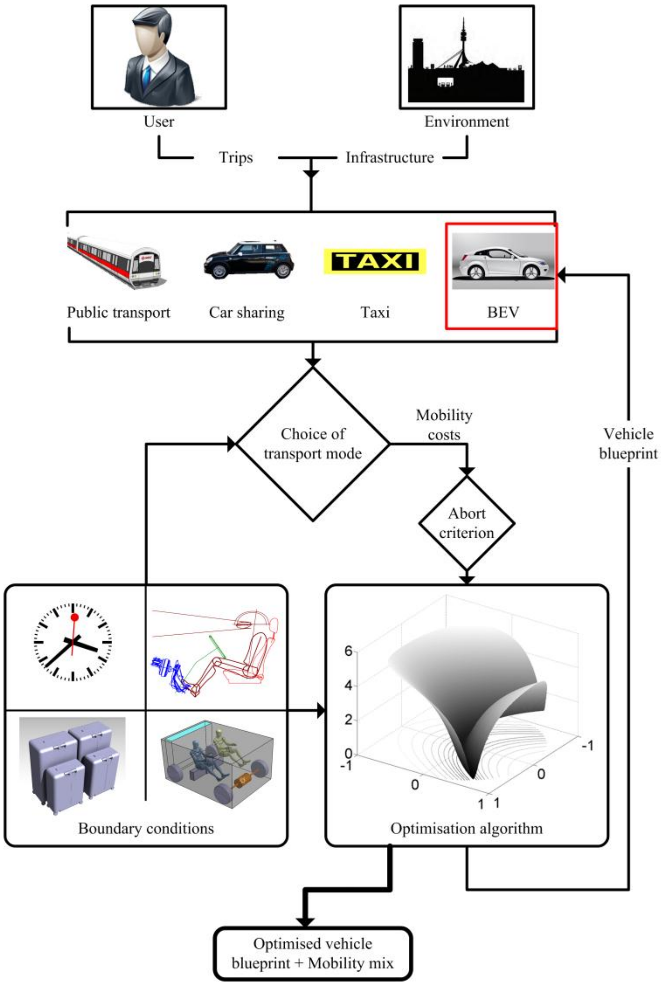

Figure 4: Optimisation process

The process starts with the selection of one user's trips over a certain period of time. This time period should be long enough to cover also irregular events, such as holiday trips or long business trips. The second input is the environment the trips are taken in. It is divided into four areas: climate, legal regulations, infrastructure and technologies.

Climate influences the selection and the energy demand of the vehicle's air conditioning system and can affect the choice of battery cells.

Legal regulations can be, for example, taxes on energy, CO_2 emissions, prohibition of cars in city centres or subsidisation of electric cars.

Infrastructure is a model of the public transport system, available car sharing offers and the taxi system.

The Technology block is a library of available components and manufacturing methods for BEVs. When the BEV is assembled later in the optimisation process, only components and techniques that are stored in this library can be used. The library includes technical properties, costs and a CO_2 footprint of every part and process if applicable.

Usually the environment information is trip-specific, because every trip has been taken in a specific environment. Here the environment block is separated from the trips in order to be able to analyse different scenarios.

In step 2, every trip in the database is simulated with the public transport model, the car sharing model, the taxi model and an energy consumption model for the BEV. The output of these models are the cost and the duration of each trip. In step 3, this data is forwarded to a decision box. In this box several knockout criteria for every mode of transportation and every trip are checked. These are the duration of the trip, the amount of luggage, availability and the range in the case of the BEV. If any of these criteria are not met, the corresponding mode of transport is excluded for the actual trip. The modes of transport are modelled in such a way, so that at least the taxi is always possible. This decision process is carried out for every trip separately. The costs of the respectively cheapest remaining mode of transport are added up and then passed to the optimisation algorithm. In step 4, the optimisation algorithm varies the optimisation parameters in order to minimise the total mobility costs while staying within the limits that are defined in the boundary condition block. The optimised parameters fully describe the BEV. These are geometrical parameters, different layouts for drivetrain and interior, component selections and component dimensioning. The behaviour of the other modes of transport or their selection is not optimised directly. The performance of the BEV influences the choice of transport mode indirectly. The rateable costs, which are the total costs of ownership for the BEV per month plus the additional costs for public and shared transport, are optimised by the target function itself. The non-rateable properties are kept as fixed boundary conditions. That way the optimised solution has to stay within these given boundaries.

Steps 2, 3 and 4 are carried out until no better configuration for the BEV can be found. The detailed abort criteria are described in Chapter 5. The results of the optimisation process are analysed in the post processing block. The direct result is the blueprint for the BEV. The indirect result is the mobility mix as an outcome of the decision block.

3. MODELLING

In order to calculate the trip properties, simulation models for the BEV, the car sharing and the taxi are required. This chapter describes the setup of these models. A detailed model for public transport has not been implemented yet. All implementations are done in Matlab. The model input is the transport task, which is given through the trip database as described in Chapter 2. Based on this input and the model's behaviour, the duration of the journey and the transport costs are calculated. In order to be able to compare the modes of transport, the output has to have the same structure for every model.

3.1 BEV model

The BEV´s properties are represented through a longitudinal dynamics simulation model and a computer aided design (CAD) model. The longitudinal dynamics model describes the vehicle's performance and energy flow. Its topology is based on the physical vehicle structure. Different model behaviours are achieved through the model's parameterisation. This parameterisation derives from the vehicle setup, which is varied by the optimisation algorithm during the optimisation run. The vehicle setup fully determines the vehicle, but does not include every parameter needed for the model's parameterisation. The transformation of the vehicle setup to the model parameter set is done in the vehicle assembly block. An overview of this structure is given in Figure 5.

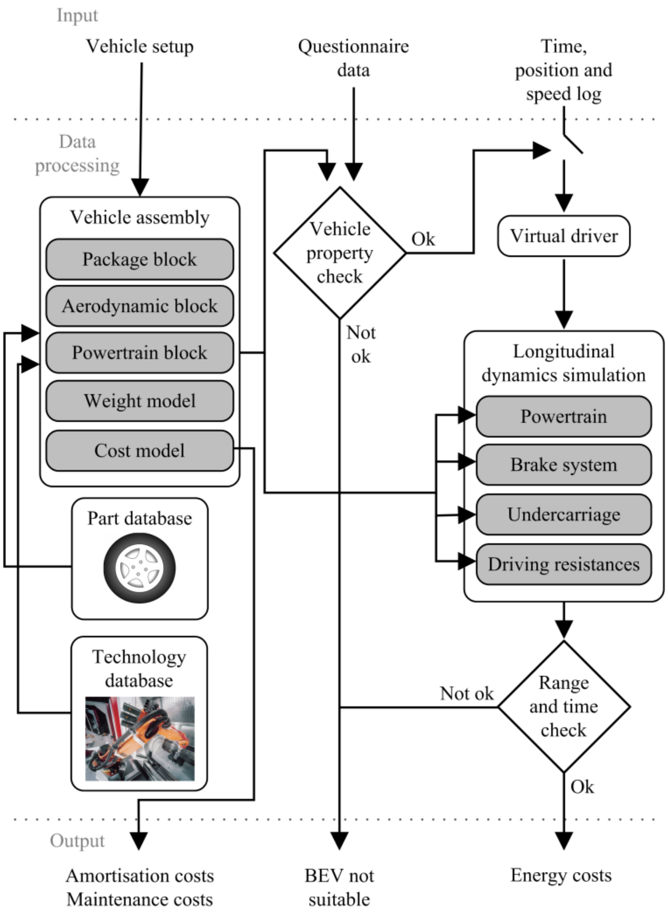

Figure 5: BEV model

In the first step of data processing, the vehicle setup is transferred to a full model parameter set in the vehicle assembly block. This block is clustered into five modules.

The package module includes the calculation of the gross weight, the position of the centre of gravity and the derivation of the main dimensions of the vehicle and every component. The geometric compatibility of all components is modelled as a boundary condition of the optimisation algorithm.

The aerodynamic block uses a correlation between the vehicle's length , width and height to calculate the frontal area and the drag coefficient [2].

In the “Powertrain” block, the electric motor, the inverter and the battery are combined. The vehicle setup dataset controls which motor is selected from the part database. The electrical, mechanical and geometrical properties of the motor are then written into the model parameterisation files. The same procedure is carried out for the inverter and the battery cells. Beginning with the motor, only compatible inverters can be selected. Motor and inverter are treated as one unit, because the efficiency of the inverter is influenced by the motor and the other way around. Based on the maximum rated voltage of the inverter and the available package space for battery cells, the battery interconnection is calculated. The algorithm connects as many cells in series as possible without exceeding the rated voltage of the inverter in order to achieve the best possible efficiency. Voltage limitations due to safety regulations are not taken into account. If this is an important aspect, only inverters with safe voltage limits should be in the database.

The task of the weight module is to pass the weight of every vehicle component to the package module. For some components, the weight is independent from the vehicle setup. Their data is taken from the “Part” database. The other parts are scaled to the vehicle's size. Those components are the vehicle structure, the undercarriage, the exterior and the interior. The scaling laws are described in [4]. For the battery, a specific energy density of 130 Wh/kg is assumed [5].

The cost module is equivalent to the weight module. The total costs of the vehicle are passed to the target function of the optimization algorithm. The input data for the vehicle structure is taken from [4]. The battery costs are set to 300€/KWh for LiFePo4 cells [5].

Once the parameterisation is complete, the trip data is simulated with the longitudinal dynamics model. This is a one dimensional point mass model with a variable step size Euler solver. The battery model uses an electric equivalent circuit with a voltage source, an ohmic resistance, an RC circuit and two 2 Warburg impedances [6].

In order to guarantee the geometric compatibility of all components, a package model is added to the longitudinal simulation model. It includes volume models of the battery, the motor, the passengers and the trunk. Figure 6 shows one possible layout of the package model.

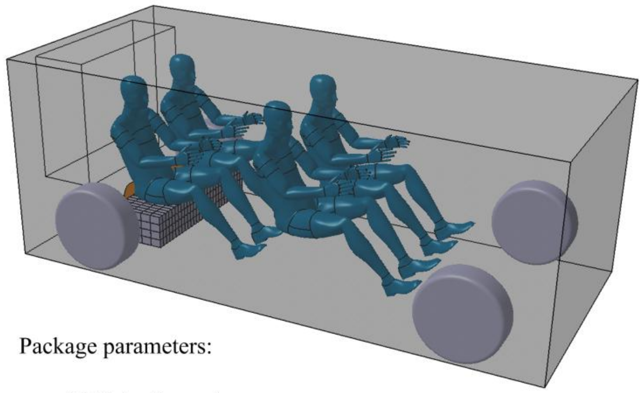

Figure 6: Package model

The package model has a modular structure in order to represent a wide spectrum of vehicle layouts. This goes from one seat row to two rows in the interior and a front or rear wheel drive setup of the powertrain to several possible battery layouts.

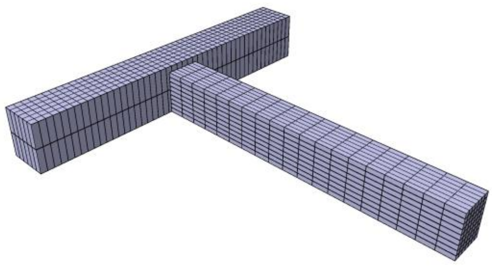

Figure 7: Battery volume

The battery volume shown in Figure 7 is modelled with two fully parametric boxes. For some configurations, the second box can be deactivated. This allows for the reproduction of batteries with under floor layout through to middle tunnel layouts and up to a T-shaped layout. The dimensions and possible orientations of the cells are read from the part database and can vary as well. The package model itself does not have any logic to control the packaging process. It gives feedback about volume intersections and the centre of gravity to the constraint function of the optimisation algorithm.

3.2 Car sharing model

The main task of the car sharing module is the fee calculation. The journeys are taken from the trip database plus an average five minute walk to the next car. The model supports the calculation of a starting fee, a minute fee, a parking fee and a check for the business district. Figure 8 shows the structure of the car sharing model.

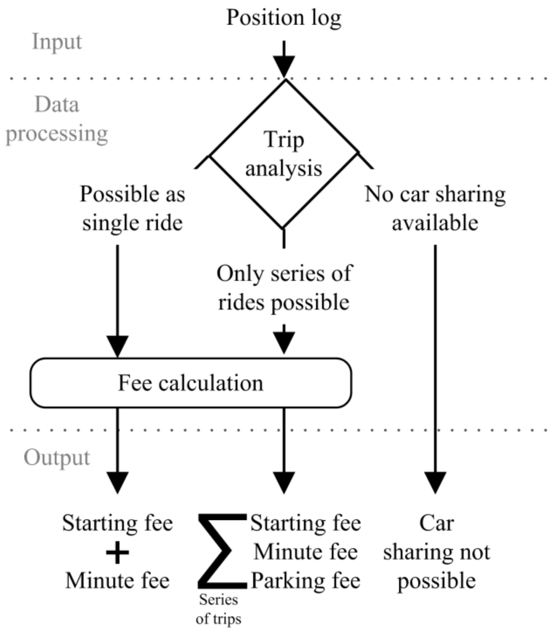

Figure 8: Car sharing model [7]

The first step is a decision block analysis on whether car sharing is available for the evaluated trip. If the start and end points are within the business district of the car sharing provider, a single ride is possible. There are no knockout criteria for the amount of passengers or luggage. The output costs are the sum of the starting fee and the minute fee.

If only the start point is within the business district, the resulting trips are checked for a trip chain. A trip chain starts and ends in the business district, but trips in between can be outside the district. The start and end points of two connected trips may not be more than 500 meters apart from each other. The output costs of a trip series are the sum of the starting fee, all minute fees and all parking fees.

If neither a single ride, nor a series of rides is possible, car sharing is excluded.

3.3 Taxi model

The third mode of transport that is modelled is the taxi. Figure 9 shows the structure of the taxi model.

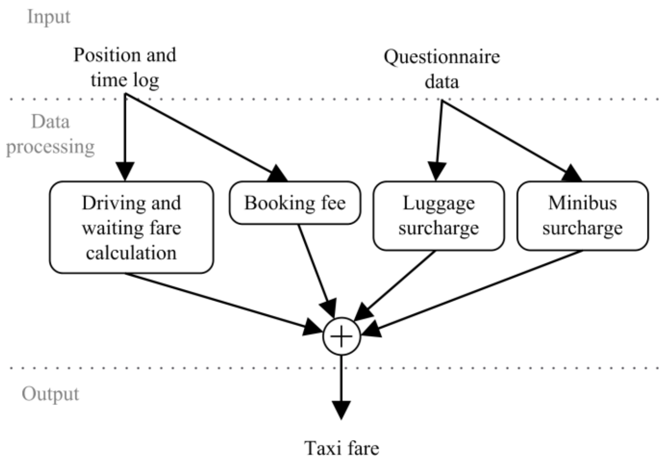

Figure 9: Taxi model [7]

Assuming that calling a taxi is always possible, there is no availability check required. The fare consists of the booking fee, driving and waiting fees and luggage or minibus surcharges. The ratio of driving to waiting is calculated from the recorded trips. Booking fees and meter rates are dependent on the start time of the trips. Based on the questionnaire data, luggage and minibus surcharges are applied.

4. BOUNDARY CONDITIONS

The boundary conditions that are applied during the optimisation process, according to Figure 3, can be split into the ones that influence the selection of the mode of transport and the ones that influence the creation of optimisation parameters.

The selection of the mode of transport is based on the costs, unless one knockout criterion is valid.

For the BEV, four knockout criteria are defined:

- Remaining range
- Number of seats
- Amount of luggage
- Trip duration

Prior to simulation of the trip is started, the seat and luggage capacity of the vehicle setup is checked. If this check is passed, the simulation is carried out. The results are checked for the remaining range and the trip duration. The range must be at least 20 km longer than the original trip, the travel time must not exceed 130% of the original trip. This occurs when the motor of the BEV is too weak to maintain the speed of the original trip.

As described in Chapter 3, the car sharing model checks for the business district for every trip. Only trips within the business district or series of trips that start and end in the business district are valid.

There are no knockout criteria defined for the taxi. This mode of transport is always possible.

The second group of boundary conditions influences the creation of the optimisation parameters in order to maintain a valid vehicle parameter set. There are linear and nonlinear boundary conditions. According to Eq. (1), linear boundary conditions describe a linear relation between two or more optimisation parameters like

$$A\,x \leq b\,. \tag{1}$$

The cross product of the user defined matrix *A* and the optimization parameter vector *x* must be smaller than the vector *b*. This type of boundary condition is used for fix dimension chains in the vehicle package. One example is the width of the battery box.

$$\begin{pmatrix}-1 & 1\end{pmatrix} \times \begin{pmatrix}Vehicle\ width \\ Battery\ width\end{pmatrix} \leq \text{-}Crash\ length\ side \tag{2}$$

Since the vehicle package is subject to optimisation, not every dimension chain can be predefined. In order to optimise the vehicle package, nonlinear boundary conditions are used. A nonlinear boundary condition can be any function of the optimisation parameters.

$$Nonlinear\_constraint\_function(x) \leq 0 \tag{3}$$

For the package optimisation, function (3) returns the intersection volume of all boundary surfaces of the package model shown in Figure 10. If there are no clashes, the constraint function returns zero and the vehicle setup is valid. In order to have a good performance, the boundary volumes are simple polygons. Thus, the intersection check can be done in a Matlab function. The CAD system CATIA serves as a visual output for the user. The bodies that are modelled with boundary boxes are the passengers, their field of view, the battery, the motor and the luggage.

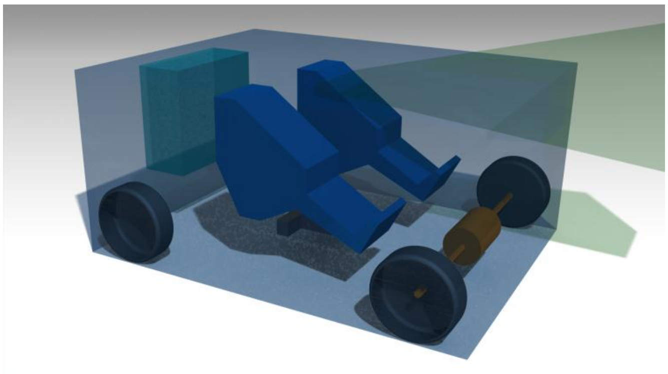

Figure 10: Boundary box model

5. PROBLEM CHARACTERISATION AND OPTIMISATION

Before selecting the optimisation algorithm, the problem has to be characterised. This characterisation is done with several attributes of the optimisation parameter space and characteristics of the target function. Topics of interest are:

- Type of the expected minimum
- Continuity of the target function
- Type of optimisation parameters

The first question is whether the target function has only one global minimum or several local minima as well. While local search algorithms only search at one point until they reach an optimum, global search algorithms evaluate multiple points in parallel in order to find the global optimum. As, for this optimisation problem, the target function is a mix of four different modes of transportation and different vehicle topologies, several local minima for different vehicle topologies are expected. In order to find the global minimum, a global search algorithm is required.

The next aspect to look at is the continuity of the target function. In this case it is discontinues. Discontinuities occur, when for example the mode of transport changes or when the components or technologies of the BEV are changed. These changes activate different cost models and create steps in the target function. Discontinuous target functions require an optimisation algorithm that works without gradients.

Another aspect is the type of optimisation parameters. Linear optimisation algorithms only work with continuous optimisation parameters. The problem described in Chapters two and three is a mix of continuous and discrete parameters. The vehicle dimensions or the battery size are continuous, while the number of seats or the selection of battery cells is discrete.

As the target function is strongly nonlinear, linear optimisation algorithms are not suitable. By a process of elimination, a genetic optimisation algorithm was selected. This optimisation algorithm performs well on strongly nonlinear problems with discontinuous target functions, multiple local minima and mixed optimisation parameters. The algorithm has proven its potential in similar vehicle concept problems [10, 11]. One drawback of the genetic optimisation algorithm is that it needs more iteration to find a minimum than a more specialised one. Therefore, parallel computing is used to compensate this drawback in the present approach.

Figure 11 illustrates the structure of the genetic algorithm used.

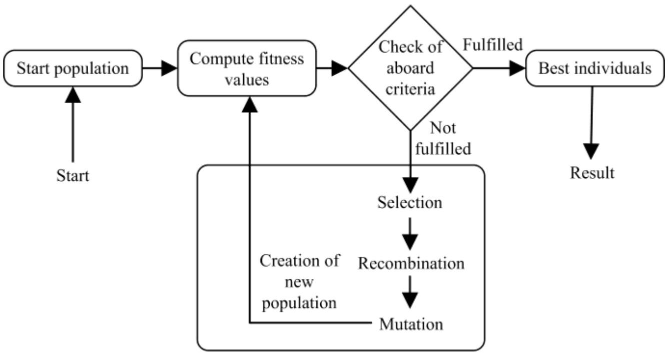

Figure 11: Structure of a genetic optimisation algorithm [8]

The optimisation process begins with the initialisation of a start population. The parameter values are assigned randomly within the specified parameter space. In the next step, the fitness value for every individual is calculated according to the target function described in Chapter three. Subsequently, the aboard criteria are checked. There are three different criteria defined:

- Maximum number of iterations
- Maximum number of iterations without improvement of the fitness value
- Minimum improvement of the fitness value per iteration

These criteria are adjusted in such a way as to give a good compromise between the calculation time and the quality of the solution. If the algorithm stops too early, the result might not be the global minimum. While the aboard criteria are not fulfilled, new generations are created by selection, recombination and mutation. Recombination and mutation allow the development new attributes that have not been in the initial population. In Figure 12, the total mobility costs of the best individual of the respective generation are plotted versus the generation count. The population size in this optimisation run is 500.

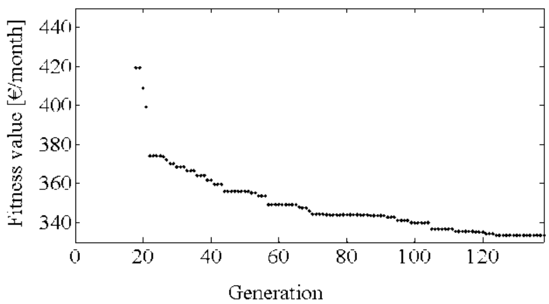

Figure 12: Convergence diagram of the optimisation process

Every dot represents the best individual of each generation. The optimisation process converged after 130 iterations. The first 20 iterations are needed to find the first solution that complies with the boundary conditions. In the area of the horizontal lines, the best individual does not improve, but the whole population does. At some point, also the combination of two good individuals may result in an improved fitness value. At generation 140, the improvement of the best individual is below the defined limit and the mean fitness of the population is close to the best individual. This indicates with a high probability that a global optimum is reached. The optimisation process is aborted.

6. CONCLUSION

For the results shown in this paper, one vehicle setup for one user was optimised. This user recorded 560 trips over a time period of 17 months. All recorded trips have been used for the optimisation. The parameters of the initial population were set randomly. After 40 hours of calculation time on a desktop computer with eight cores, the optimisation process was completed by the aboard criteria. The parameters of the best individual of the last generation were stored. This is where the global optimum is supposed to be. These parameters have been used to assemble the vehicle shown in Figure 13. The vehicle would belong to the user. The amortisation costs are calculated for a lifetime of 6 years.

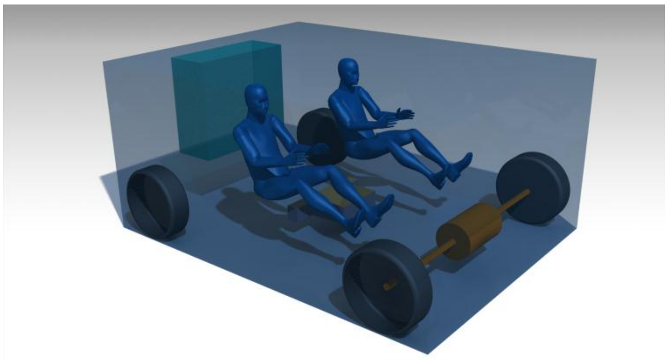

Figure 13: Optimised vehicle package

The vehicle is a two-seater with front wheel drive and a small trunk. Table 1 shows the main characteristics.

Table 1: Vehicle characteristics

Item	**Value**
Length	3.2 m
Width	1.8 m
Height	1.5 m
Curb weight	1063 kg
Drive axle	Front wheel drive
Motor power	78 kW
Energy efficiency	20 kWh/100km
Battery capacity	25 kWh
Range	120 km

The front wheel drive allows package space for the trunk. The power of the motor is sufficient to keep up with the velocities of the recorded trips and thus maintain a duration not more than 30% longer than the original trip. The power of the motor is quite high, because the trips include some rides with a top speed of 160Km/h. The part database does only include three different motor sizes yet. A motor one step smaller with 39KW would be too weak.

But this vehicle setup is not sufficient for all trips. Figures 14 and 15 show the original modal split with the conventional car and the optimised modal split. In the optimised solution, the user does not own a conventional car any more. The original trips were recorded by car, foot and bicycle only. The number of trips done by foot and bicycle stays constant, because they were excluded from the optimisation process. There is not enough information available for this decision. The 84% that have been taken by car are divided between the BEV, car sharing and taxi. The BEV has high initial costs, but very low running costs. As the initial costs of the BEV are always included in the target function, this is the best selection for a trip. But for some trips, the knockout criteria of Chapter 4 apply. For 17% of the trips, the number of seats is too small and for 6.7% the trunk is too small. For only 3.5% of the remaining trips, the range is the knockout criterion. This shows that the optimisation process lead to a sufficient battery size for most of the trips. There is no visible correlation between all knockout criteria. This illustrates the vehicle design problem mentioned in the introduction. The car sharing solution provides the second lowest costs, but is only available within the business district. The remaining trips have to be taken by taxi. The optimised solution shows a scenario for the user without the ownership of a personal conventional car. The costs are higher than the original costs, but the lowest possible costs with the given environment. With the implementation of the public transport model, the taxi segment will be reduced.

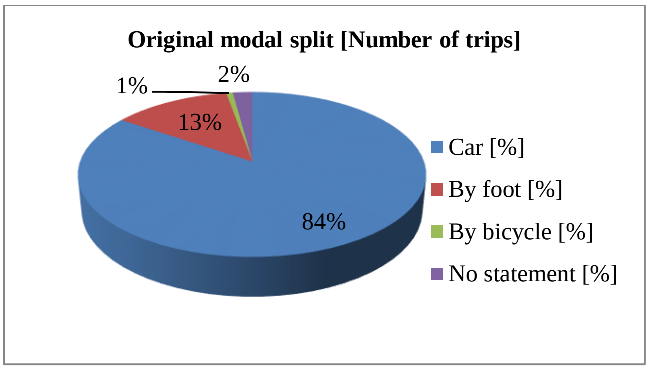

Figure 14: Original modal split

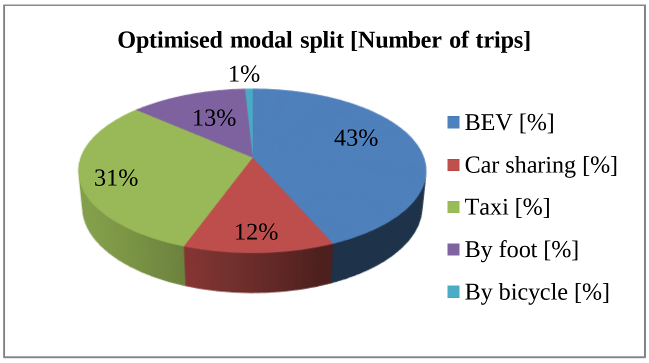

Figure 15: Optimised modal split

The focus of this paper rests on the description of the optimisation problem itself, not on the analysis of the optimisation results. The presented vehicle setup and modal split is only a sample of one user. A single user result could assist the individual person to find a suitable vehicle configuration for his environment. This might be the selection of a suitable vehicle size or battery size.

7. SUMMARY AND OUTLOOK

Beginning with the conflict of goals between vehicle performance, energy efficiency and BEV costs, this paper highlights the need for a modal split and its consideration during the vehicle planning phase. Chapter 2 describes a process of how a multimodal optimisation can be implemented. The input of this optimisation algorithm is user behaviour, which is given through a track database. The optimisation target is the total mobility costs for the user. Chapter 3 describes how these costs are calculated in a longitudinal simulation model for the BEV, a car sharing model and a taxi model. In order to generate a consistent vehicle concept; package, battery, weight, aerodynamics, and costs models are used to complete the longitudinal simulation model. In Chapter 4, several boundary conditions are introduced. They control soft factors like travel time, level of comfort and driving dynamics and ensure a valid vehicle package. A characterisation of the optimisation problem is done in Chapter 5. Based on these characteristics, a genetic optimisation algorithm is introduced. Chapter 6 discusses the results of an optimisation run for one user and shows a possible use case.

The discussed results are not yet sufficient to give the required input during the vehicle planning phase, because the optimisation has only been done for one user. In the next step, the goal will be to identify users with equal requirements and optimise one vehicle setup for multiple users. As this will multiply the calculation demand, parallel computing with multiple desktop computers or a mainframe computer has to be implemented. The genetic algorithm is suitable for parallel computing, because the fitness calculation of the individuals of one generation can be distributed to several clients.

The presented tool can not only be used to investigate vehicle topologies, it can show the influences of different environments as well. Through the separation of user demand from the infrastructure, different scenarios can be analysed. A Pareto optimisation, where the total CO_2 emissions are the second optimisation target, can show which measures for the reduction of emissions are most cost efficient.

8. ACKNOWLEDGMENTS

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